TITLE OF THE INVENTION

CRYSTALLIZATION APPARATUS AND CRYSTALLIZATION METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from the prior Japanese Patent Applications No. 2002-351955, filed December 4, 2002; and No. 2002-357254, filed December 9, 2002, the entire contents of both of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a crystallization technology, and more particularly to an apparatus and a method which form or generate a crystallized semiconductor film by irradiating a polycrystal semiconductor film or an amorphous semiconductor film with a laser beam phase-modulated by using a phase shifter, and to a phase shifter.

2. Description of the Related Art

In general, materials of a thin film transistor (TFT) used for, e.g., a switching element which controls a voltage to be applied to pixels in, e.g., a liquid crystal display (LCD) are roughly classified into amorphous silicon and polysilicon.

The polysilicon has higher electron mobility than that of the amorphous silicon. Therefore, when a transistor is formed by using the polycrystal silicon,

a switching speed becomes higher than that when using
the amorphous silicon, and a response of a display
thereby becomes rapid. Further, a peripheral LSI can
be also constituted of such thin film transistors.

5   Furthermore, there is an advantage of reducing a design
margin of any other component. Moreover, when
incorporating peripheral circuits such as a driver
circuit or a DAC other than a display main body in
a display, these peripheral circuits can be operated at

10   a higher speed.

The polycrystal silicon consists of an aggregate
of crystal grains, and its electron mobility is lower
than that of crystallized silicon or monocrystal
silicon. In a small transistor formed by using

15   polycrystal silicon, irregularities in crystal grain
boundary number in a channel portion are a problem.
Thus, there has been recently proposed a crystalliza-
tion method to form crystallized silicon with a large
particle size in order to improve the electron mobility

20   and reduce irregularities in crystal grain boundary
number in a channel portion.

As this type of crystallization method, there is
known "phase control ELA (Excimer Laser Annealing)"
which forms a crystallized semiconductor film by

25   irradiating a line type phase shifter approximated
in parallel with a polycrystal semiconductor film or
an amorphous semiconductor film with an excimer

laser beam. The detail of the phase control ELA is disclosed in, e.g., "Surface Science Vol. 21, No. 5, pp. 278-287, 2000".

In the phase control ELA, there is generated a light intensity distribution having an inverse peak pattern or patterns that a light intensity is substantially zero or minimum in a line corresponding to a phase shift portion of a phase shifter (pattern that a light intensity is minimum at the center and it is suddenly increased toward the periphery), and a polycrystal semiconductor film or an amorphous semiconductor film is irradiated with a light beam having this light intensity distribution with the inverse peak pattern. As a result, a temperature gradient is generated in a fusing area in accordance with the light intensity distribution, a crystal nucleus or nuclei are formed at a part or parts which solidify first in accordance with a point or points on a line where the light intensity is minimum or substantially minimum, and a crystal grows towards the periphery from the crystal nucleus in a lateral direction (lateral growth), thereby forming a crystal nucleus with a large particle size.

As shown in FIGS. 1A and 2A, the line type phase shifter is constituted of two types of rectangular areas 101a and 101b having different thicknesses which are alternately repeated along one direction (lateral

direction) of a transparent substrate 100, and a phase

difference of π (180 degrees) is given to a gap between

the adjacent areas, i.e., a step portion 101c.

As shown in FIG. 1B, a light beam which has passed

through such a phase shifter forms a light intensity

distribution with an inverse peak pattern that a light

intensity is minimum on a line 102 corresponding to

a phase shift portion (boundary) 101c and the light

intensity is one-dimensionally increased toward the

periphery in a direction orthogonal to the line 102.

FIG. 2B concretely shows this light intensity

distribution.

When a processed substrate is irradiated with

the light having such a light intensity distribution,

a temperature distribution becomes lowest along the

line 102 corresponding to the phase shift portion 101C,

and a temperature gradient (indicated by each arrow in

the drawing) is generated in a direction orthogonal to

the line 102 corresponding to the phase shift portion.

As a result, each crystal nucleus 103 is generated on

the line 102 corresponding to the phase shift portion

101C as shown in FIG. 1C, and crystallization advances,

in a lateral direction, that is a direction orthogonal

to the line 102 corresponding to the phase shift

portion from that crystal nucleus 103. In FIG. 1C,

curves 104 indicate a crystal grain boundary, and

crystal grains are formed in an area defined by these

crystal grain boundaries 104.

In such a crystallization method, although the crystal nucleus 103 is generated on the line 102 corresponding to the phase shift portion 101C,

5   a position on the line 102 where the crystal nucleus 103 or nuclei are generated is uncertain. In other words, when the line type phase shifter is used, any position at which the crystal nucleus 103 is generated cannot be controlled by the phase shift portion, and it

10   is hence impossible to two-dimensionally control a crystal formation area.

Additionally, in the light intensity distribution obtained by using the line type phase shifter, as shown in FIG. 2B, it is general to involve irregular

15   undulations in a middle portion PM between two adjacent inverse peak pattern portions PP (wavelike distribution that an increase and a decrease in light intensity are repeated). In this case, a crystal nucleus 103b may be generated at a position where the light intensity is

20   low in undulations in the middle portion MP (i.e., at an undesired position) in some cases. Further, even if a crystal nucleus is generated at a desired position, the lateral growth which has started from the crystal nucleus toward the periphery is stopped at a part where

25   the light intensity is decreased at the boundary between the inverse peak pattern portion and the middle portion, which prevents growth of a large crystal.

BRIEF SUMMARY OF THE INVENTION

It is an object of the present invention to provide a crystallization apparatus and a crystallization method which can two-dimensionally generate

5   a crystal nucleus at a desired position and realize a sufficient lateral growth from a crystal nucleus, thereby producing a crystallized semiconductor film with a large particle size.

A crystallization apparatus according to a

10   first aspect of the present invention includes an illumination system which illuminates a phase shifter, and irradiates a polycrystal semiconductor film or an amorphous semiconductor film with a light beam having a predetermined light intensity distribution that

15   a light intensity is minimum in an area corresponding to a phase shift portion of the phase shifter, thereby forming or growing a crystallized semiconductor film. The phase shifter has a four or more even-numbered phase shift lines which intersect at a point constitut-

20   ing the phase shift portion, and an area on one side and an area on the other side of each phase shift line preferably have a phase difference of approximately 180 degrees.

The phase shifter may has a conformation that four

25   rectangular areas are arranged so as to be adjacent to each other with one apex in common. Alternatively, it is preferable that the phase shifter has a conformation

that six or more triangular areas are arranged so as to be adjacent to each other with one apex in common. Alternatively, it is preferable that the phase shifter has a conformation that it has a first phase shift portion at which even-numbered first phase shift lines intersect and a second phase shift portion at which even-numbered second phase shift lines intersect and a plurality of first phase shift portions and a plurality of second phase shift portions are alternately arranged. In this case, it is preferable that the first phase shift portion corresponds to a point at which the four phase shift lines intersect and the second phase shift portion corresponds to a point at which the eight phase shift lines intersect. Furthermore, in this case, it is preferable that the first phase shift portion corresponds to one apex provided to the four triangular areas in common and the second phase shift portion corresponds to one apex provided to the eight triangular areas in common.

Moreover, according to the first aspect, it is preferable that the polycrystal semiconductor film or the amorphous semiconductor film and the phase shifter are arranged in parallel with and in close proximity to each other. In this case, it is preferable that an outgoing radiation pupil of the illumination system has a shape that a dimension along one direction and a dimension along the other direction are substantially

different from each other. Additionally, in this case,
assuming that D is a distance between the polycrystal
semiconductor film or the amorphous semiconductor film
and the phase shifter, λ is a wavelength of a light

5   beam, θmax is a maximum incident angle of the light
upon the phase shifter along a direction that the
outgoing radiation pupil of the illumination system is
maximum and θmin is a maximum incident angle of the
light upon the phase shifter along a direction that the

10   outgoing radiation pupil of the illumination system is
minimum, it is preferable to satisfy the following
conditions:

$$D \times \tan(\theta min) < 1.2 \times (\lambda D/2)^{1/2}$$
$$D \times \tan(\theta max) > 1.2 \times (\lambda D/2)^{1/2}$$

15   Further, according to the first aspect,
preferably, the crystallization apparatus further
includes an image forming optical system arranged on
a light path between the polycrystal semiconductor film
or the amorphous semiconductor film and the phase

20   shifter, and the polycrystal semiconductor film or
the amorphous semiconductor film is set apart from
a surface optically conjugate with the phase shifter
by a predetermined distance along an optical axis of
the image forming optical system.

25   Alternatively, according to the first aspect,
preferably, the crystallization apparatus further
includes an image forming optical system which is

arranged on a light path between the polycrystal
semiconductor film or the amorphous semiconductor film
and the phase shifter, the polycrystal semiconductor
film or the amorphous semiconductor film is set to

5   a surface optically substantially conjugate with the
phase shifter, and an image side numerical aperture of
the image forming optical system is set to a value
required to generate the predetermined light intensity
distribution. In this case, it is preferable that the

10   pupil of the image forming optical system has a shape
that a dimension along one direction and a dimension
along the other direction are substantially different
from each other.

A crystallization apparatus according to a second

15   aspect of the present invention forms a crystallized
semiconductor film by irradiating a polycrystal semi-
conductor film or an amorphous semiconductor film with
a light beam having a predetermined light intensity
distribution. There is provided the crystallization

20   apparatus characterized in that the predetermined light
intensity distribution has an inverse peak point with
a light intensity lower than that at the periphery and
has two or more trough lines each of which extends from
the inverse peak point to the periphery and has a lower

25   change gradient is of the light intensity than that at
the periphery. In this case, it is preferable that the
light intensity distribution along the trough lines has

an inflection point.

A crystallization method according to a third aspect of the present invention illuminates a phase shifter, and irradiates a polycrystal semiconductor film or an amorphous semiconductor film with a light beam having a predetermined light intensity that a light intensity is minimum in an area corresponding to a phase shift portion of the phase shifter, thereby forming a crystallized semiconductor film. This method may use a phase shifter which has four or more even-numbered phase shift lines which intersect at a point constituting the phase shift portion and in which an area on one side and an area on the other side of each phase shift line have a phase difference of approximately 180 degrees.

According to the third embodiment, it is preferable to arrange the polycrystal semiconductor film or the amorphous semiconductor film and the phase shifter in parallel with and in close proximity to each other. Alternatively, it is preferable that an image forming optical system is arranged on a light path between the polycrystal semiconductor film or the amorphous semiconductor film and the phase shifter, and a surface of the polycrystal semiconductor film or the amorphous semiconductor film is set apart from a surface optically conjugate with the phase shifter by a predetermined distance along an optical axis of the

image forming optical system. Alternatively, it is
preferable to arrange the image forming optical system
on the light path between the polycrystal semiconductor
film or the amorphous semiconductor film and the phase

5   shifter, set an image side numerical aperture of the
image forming optical system to a value required to
generate the predetermined light intensity distribu-
tion, and set the polycrystal semiconductor film or the
amorphous semiconductor film at a position optically

10   conjugate with the phase shifter through the image
forming optical system.

A crystallization method according to a fourth
aspect of the present invention forms a crystallized
semiconductor film by irradiating a polycrystal

15   semiconductor film or an amorphous semiconductor
film with a light beam having a predetermined light
intensity distribution. The polycrystal semiconductor
film or the amorphous semiconductor film is irradiated
with a light beam having a light intensity distribution

20   which has an inverse peak point with a light intensity
lower than that at the periphery and has two or more
trough lines each of which extends from the inverse
peak point toward the periphery and has a lower change
gradient of the light intensity than that at the

25   periphery.

A phase shifter according to a fifth aspect of the
present invention has four or more even-numbered phase

shift lines which intersect at a point constituting a phase shift portion, and an area on one side and an area on the other side of each phase shift line have a phase difference of approximately 180 degrees.

According to the fifth aspect, it is preferable that four rectangular areas preferably have a conformation that they are arranged so as to be adjacent to each other with one apex in common. Alternatively, it is preferable that six or more triangular areas have a conformation that they are arranged so as to be adjacent to each other with one apex in common. Alternatively, it is preferable to have a conformation that there are a first phase shift portion at which even-numbered first phase shift lines intersect and a second phase shift portion at which even-numbered second phase shift lines intersect, and a plurality of first phase shift portions and a plurality of second phase shift portions are alternately arranged. In this case, it is preferable that the first phase shift portion corresponds to a point at which the four phase shift lines intersect and the second phase shift portion corresponds to a point at which the eight phase shift lines intersect. Furthermore, in this case, it is preferable that the first phase shift portion corresponds to one apex provided to the four triangular areas in common and the second phase shift portion corresponds to one apex

provided to the eight triangular areas in common.

As described above, in the technology according to the present invention, since there is used the phase shifter which has four or more even-numbered phase shift lines intersecting at a point constituting the phase shift portion and in which an area on one side and an area on the other side of each phase shift line have a phase difference of approximately 180 degrees, a crystal nucleus can be generated in an area corresponding to the phase shift portion, and a defocus effect or a blurring effect which is relatively larger than that of the line type phase shifter can be added. Therefore, the light intensity distribution in the area corresponding to the phase shift portion does not involve irregular undulations. Accordingly, the lateral growth which has started from the crystal nucleus toward the periphery does not stop in mid course, and a single crystal or polycrystal with a large particle size can be generated. As a result, in the present invention, a crystal nucleus or a crystal growth start point can be produced at a desired position, the sufficient lateral growth from the crystal nucleus can be realized, thereby generating a crystallized semiconductor film with a large particle size.

Objects and advantages of the invention will be set forth in the description which follows, and in part

will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and

5   combinations particularly pointed out hereinafter.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention, and together

10   with the general description given above and the detailed description of the embodiments given below, serve to explain the principles of the invention.

FIGS. 1A to 1C are views illustrating a structure and an effect of a conventional line type phase

15   shifter, in which FIG. 1A is a plane view of a basic unit part of a phase shifter (hatching is used in order to clarify a difference from another area, does not show a cross section, and is used in any of the following figures for the same purpose), FIG. 1B is a

20   view showing a crystal growth direction on a processed substrate, and FIG. 1C is a view showing crystal grains and crystal nuclei to be formed;

FIGS. 2A and 2B are views respectively showing a line type phase shifter and a light intensity

25   distribution obtained by using the phase shifter;

FIG. 3 is a view schematically showing a structure of a crystallization apparatus according to a first

embodiment of the present invention;

FIGS. 4A to 4C are views schematically showing a structure and an effect of a basic unit part of the phase shifter according to the first embodiment, in which FIG. 4A is a plane view of the basic unit part of the phase shifter; FIG. 4B is a view showing a light intensity distribution on the processed substrate, and FIG. 4C is a view showing crystal grains and crystal nuclei to be formed;

FIG. 5 is a view typically showing a light intensity distribution obtained on the processed substrate by using the phase shifter shown in FIG. 4A by contour lines in the first embodiment;

FIGS. 6A to 6C are views illustrating a primary structure and an effect of a crystallization apparatus according to a first modification of the first embodiment, in which FIG. 6A is a view showing a relationship between an outgoing radiation pupil of an illumination system, a phase shifter and a processed substrate, FIG. 6B is a view showing a light intensity distribution on the processed substrate, and FIG. 6C is a view showing crystal grains and crystal nuclei to be formed;

FIG. 7 is a view typically showing a light intensity distribution obtained on the processed substrate by using the phase shifter depicted in FIG. 4A in the first modification of the first

embodiment;

FIG. 8 is a view illustrating dimensions of the outgoing radiation pupil of the illumination system required in the modification of the first embodiment, and further showing the phase shifter and a light intensity distribution;

FIG. 9 is a view schematically showing a structure of a crystallization apparatus according to a second embodiment of the present invention;

FIG. 10 is a view schematically showing a structure of a crystallization apparatus according to a third embodiment of the present invention;

FIGS. 11A to 11C are views illustrating a primary structure and an effect of a crystallization apparatus according to a modification of the third embodiment, in which FIG. 11A is a view showing a relationship between an outgoing radiation pupil of an illumination system, a phase shifter and a processed substrate, FIG. 11B is a view showing a light intensity distribution on the processed substrate, and FIG. 11C is a view showing crystal grains and crystal nuclei to be formed;

FIG. 12 is a view schematically showing another conformation of the phase shifter applicable to each embodiment and each modification;

FIGS. 13A to 13C are views schematically showing a structure and an effect of still another conformation of the phase shifter applicable to each embodiment and

each modification, in which FIG. 13A is a view showing
a relationship between an outgoing radiation pupil of
an illumination system, a phase shifter and a processed
substrate, FIG. 13B is a view showing a light intensity
distribution on the processed substrate, and FIG. 13C
is a view showing crystal grains and crystal nuclei to
be formed;

FIG. 14A is a view typically showing a light
intensity distribution obtained on the processed
substrate by using the phase shifter depicted in
FIG. 13 by contour lines in the first embodiment,
and FIG. 14B is a view showing a light intensity
distribution taken along the line 14B-14B in FIG. 14A;

FIGS. 15A and 15B are views schematically showing
a structure and an effect of a basic unit part of
a phase shifter used in a second modification of the
first embodiment, and FIG. 15C is a view typically
showing a light intensity distribution obtained on
the processed substrate by using the phase shifter
illustrated in FIG. 15A;

FIGS. 16A and 16B are views schematically showing
a structure and an effect of a phase shifter used in
a third modification of the first embodiment;

FIGS. 17A and 17B are views schematically showing
a structure and an effect of a phase shifter which can
be used in a crystallization apparatus according to
a fourth modification of the first embodiment;

FIG. 18 is a view illustrating a magnitude of a shaped width W required for a meandering second phase shift line in the second to fourth modifications; and

FIGS. 19A to 19E are process cross-sectional views
5   showing processes to manufacture an electronic device by using the crystallization apparatus according to each embodiment.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments according to the present invention
10   will now be described with reference to the accompanying drawings.

FIG. 3 is a view schematically showing a structure of a crystallization apparatus according to a first embodiment of the present invention. The crystalliza-
15   tion apparatus according to the first embodiment includes an illumination system 2 which illuminates a phase shifter 1. The illumination system 2 includes a KrF excimer laser beam source 2a which emits a light beam having a wavelength of, e.g., 248 nm. As the
20   light source 2a, any other appropriate light source such as an XeCl excimer laser beam source can be also used. The laser beam emitted from the light source 2a is expanded through a beam expander 2b, and then enters a first fly-eye lens 2c.
25   A plurality of small light sources are formed on a rear focal plane of the first fly-eye lens 2c in this manner, and an incident plane of a second fly-eye lens

2e is illuminated with a light flux from the plurality of light sources through a first condenser optical system 2d in the superimposed manner. As a result, more small light sources than those on the rear focal

5 plane of the first fly-eye lens 2c are formed on a rear focal plane of the second fly-eye lens 2e. The phase shifter 1 is illuminated in the superimposed manner with a light flux or beam from the plurality of light sources formed on the rear focal plane of the second

10 fly-eye lens 2e through a second condenser optical system 2f.

The first fly-eye lens 2c and the first condenser optical system 2d constitute a first homogenizer, and the first homogenizer performs equalization concerning

15 incident angles on the phase shifter 1. Further, the second fly-eye lens 2e and the second condenser optical system 2f constitute a second homogenizer, and the second homogenizer achieves equalization concerning in-plane positions on the phase shifter 1. Therefore,

20 the illumination system 2 irradiates the phase shifter 1 with the light having a substantially even light intensity distribution.

A processed substrate 3 arranged in parallel with and in close proximity to the phase shifter 1 is

25 irradiated with the laser beam supplied through the phase shifter 1. Here, the processed substrate 3 is obtained by forming an underlying film and an amorphous

silicon film on, e.g., a liquid crystal display glass
sheet by chemical vapor deposition. In other words,
the phase shifter 1 is set so as to be opposed to the
amorphous semiconductor film. The processed substrate

5   3 is held at a predetermined position on a substrate
stage 4 by a vacuum chuck or an electrostatic chuck.

        FIGS. 4A to 4C are views schematically showing
a structure and an effect of a basic unit part of the
phase shifter in the first embodiment. FIG. 5 is a

10   view typically showing a light intensity distribution
obtained on the processed substrate by using the phase
shifter depicted in FIG. 4A by contour lines in the
first embodiment. Referring to FIG. 4A, a basic unit
part 10 of the phase shifter 1 has a conformation that

15   four rectangular, preferably, square areas 10a to 10d
are arranged so as to be adjacent to each other with
one apex 10e in common. Here, with the transmitted
light in the first area 10a being determined as a
reference, a phase difference of 180 degrees is given

20   to the transmitted light in the second area 10b and the
transmitted light in the fourth area 10d, and a phase
difference relative to the first area 10a is not
given (phase difference of 0 degrees is given) to the
transmitted light in the third area 10c. Since the

25   first area 10a and the third area 10c are in phase and
the second area 10b and the fourth area 10d are in
phase, the former is indicated by a white space and

the latter is indicated by hatching in FIG. 4A for better understanding.

In the rectangular, preferably, square basic unit part 10, a boundary between the first area 10a and the second area 10b constitutes a first phase shift line 10f, a boundary between the second area 10b and the third area 10c constitutes a second phase shift line 10g, a boundary between the third area 10c and the fourth area 10d constitutes a third phase shift line 10h, and a boundary between the fourth area 10d and the first area 10a constitutes a fourth phase shift line 10i. These phase shift lines 10f, 10g, 10h and 10i intersect at the center of the basic unit part 10 and constitute an apex 10e. The apex 10e is a phase shift point or a phase shift portion. As a result, the basic unit part 10 has the four phase shift lines 10f to 10i which intersect at the phase shift portion 10e, and an area on one side and an area on the other side of each phase shift line has a phase difference of 180 degrees.

Specifically, when the phase shifter is formed of, e.g., quartz glass having a refractive index of 1.5 relative to the light having a wavelength of 248 nm, a step of 248 nm is given between the first area 10a and the second area 10b, between the second area 10b and the third area 10c, between the third area 10c and the fourth area 10d and between the fourth area 10d and the first area 10a, respectively. The phase shifter 1 is

constituted by one-dimensionally or two-dimensionally arranging a plurality of basic unit parts 10 according to needs. In the phase shifter 1, its phase shift surface (irregular pattern) is preferably formed on a surface opposed to the processed substrate 3.

When the phase shifter 1 and the processed substrate 3 are arranged so as to be appressed against each other, a cruciform light intensity distribution having a relatively low light intensity is formed at a part corresponding to the four phase shift lines 10f to 10i. However, in the first embodiment, since the phase shifter 1 and the processed substrate 3 are arranged in close proximity to each other, there is formed a predetermined light intensity distribution that a light intensity is minimum in a light irradiation area corresponding to the phase shift portion 10e or a point 11 and the light intensity is relatively low in a cruciform light irradiation area corresponding to the four phase shift lines 10f to 10i or lines 12 by a so-called defocus effect (blurring effect). FIGS. 4B and 5 show that the minimum light intensity point 11 is the center and the weak light intensity area 12 extends crosswise from the minimum light intensity point 11.

The light intensity distribution depicted in FIG. 5 typically shows a simulation result obtained based on a specific numerical example. In this

numerical example, it is assumed that each of the areas
10a to 10d of the phase shifter 1 has a square shape
of 5 μm $\times$ 5 μm, a wavelength λ of the light is 248 nm,
a distance D between the phase shifter 1 and the
5   processed substrate 3 is 48 μm and a surface light
source formed to an outgoing radiation pupil (rear
focal plane of the second fly-eye lens 2e) of the
illumination system 2 has a circular shape (i.e., a
circular illumination). An area 12 with a relatively
10   weak intensity extends in directions indicated by
arrows (which become a crystal growth direction), and
the intensity becomes higher in areas on both sides of
the area 12 as distanced from the line area 12.

Therefore, in the first embodiment, as shown
15   in FIG. 4C, a crystal nucleus 13 can be formed in an
area 11 corresponding to the phase shift portion 10e.
At this time, as compared with the line type phase
shifter, since the four phase shift lines intersect at
the phase shift portion 10e, the inverse peak pattern
20   is hard to be eliminated even if a large defocus effect
is given. On the contrary, in the first embodiment,
the large defocus effect can be given, and irregular
undulations (wavelike distribution that an increase and
a decrease in light intensity are repeated) can be
25   thereby eliminated from the light intensity distribu-
tion in the cruciform area 12 corresponding to the four
phase shift lines 10f to 10i. As a result, crystal

grain 14 with a large particle size are generated
without stopping in mid course the lateral growth which
has started crosswise from the crystal nucleus 13
toward the periphery in the four directions. Thus, in

5   the first embodiment based on a so-called proximity
method (defocus method), the crystal nucleus can
be generated at a two-dimensional position (in
directions X and y) of the processed substrate, and
the sufficient lateral growth can be realized from

10   the crystal nucleus, thereby producing a crystallized
semiconductor film with a large particle size.

        FIGS. 6A to 6C are views showing a primary
structure and an effect of a crystallization apparatus
according to a first modification of the first

15   embodiment. FIG. 7 is a view typically showing a light
intensity distribution obtained on the processed
substrate by using the phase shifter depicted in
FIG. 4A in the first modification by contour lines.
Although the modification shown in FIG. 6A has

20   a structure similar to the first embodiment, it is
basically different from the first embodiment in that
the outgoing radiation pupil of the illumination system
has a shape that a dimension along one direction and
a dimension along the other direction are substantially

25   different from each other. Taking notice of the
difference from the first embodiment, the modification
will be described hereinafter with reference to

FIGS. 6A to 6C.

Referring to FIG. 6A, a surface light source 2g formed to the outgoing radiation pupil of the illumination system 2 has an elliptic shape instead of a circular shape. That is, a dimension of the outgoing radiation pupil 2g of the illumination system 2 is largest along a first direction (major axis direction) 16a, and it is smallest along a second direction (minor axis direction) 16b orthogonal to the first direction. Therefore, the defocus effect becomes maximum along the first direction 16a along which the outgoing radiation pupil 2g of the illumination system 2 is largest, and the defocus effect becomes minimum along the second direction 16b along which the outgoing radiation pupil 2g is smallest. As a result, as shown in FIGS. 6B and 7, a light intensity in an area 12a affected by the phase shift lines corresponding to the first direction 16a is higher (shallower) than a light intensity in an area 12b affected by the phase shift lines corresponding to the second direction 16b.

A light intensity distribution shown in FIG. 7 typically shows a simulation result obtained based on a specific numerical example. In this numerical example, it is assumed that each of the areas 10a to 10d of the phase shifter 1 has a square shape of 5 μm $\times$ 5 μm, a wavelength λ of the light is 248 nm and a distance D between the phase shifter 1 and the processed substrate

3 is 48 µm.   However, as different from the first

embodiment, it is assumed that a shape of the surface

light source 2g formed to the outgoing radiation

pupil of the illumination system 2 is an ellipse that

5   a major axis: a minor axis is 6:5 (i.e., an elliptic

illumination).

The light intensity distribution shown in FIG. 7

has an inverse peak point 11 with a lower light

intensity than that at the periphery, and it has two

10   trough lines (areas affected by the phase shift lines

corresponding to the second direction 16b) 12b which

extend from the inverse peak point 11 to the periphery

and have a lower change gradient of the light intensity

than that at the periphery.   That is, the area 12b

15   in which the light intensity is relatively weak in

a straight line form is formed around the minimum

intensity area 11.   Consequently, as shown in FIG. 6C,

in the modification of the first embodiment, a crystal

nucleus 13 is generated in the point area 11 corre-

20   sponding to the phase shift portion 10e like the first

embodiment.   However, as different from the first

embodiment, the lateral growth does not start along the

area 12a which is orthogonal to the linear area 12b and

has a high (shallow) light intensity, and the lateral

25   growth starts along only the area 12b having a lower

(deep) light intensity by priority.   As a result, as

different from the first embodiment, the lateral growth

advances without being affected by adjacent crystals, and hence crystal grain 14 larger than those in the first embodiment can be produced.

FIG. 8 is a view illustrating a dimension of the outgoing radiation pupil of the illumination system required in the modification of the first embodiment. Referring to FIG. 8, in the light intensity distribution formed on the processed substrate by the phase shifter 1, a half value width L of the inverse peak pattern around the phase shift point can be represented by the following expression (1). In the expression (1), as described above, λ is a wavelength of the light from the illumination system, and D is a distance between the phase shifter 1 and the processed substrate 3.

$$L = 1.2 \times (\lambda D/2)^{1/2} \qquad (1)$$

On the other hand, a defocus quantity (blurring quantity) B based on the illumination light passing through an outgoing radiation pupil end of the illumination system 2 can be represented by the following expression (2). It is to be noted that θ is the maximum incident angle of the light upon the phase shifter 1 along a direction to be considered.

$$B = D \times \tan\theta \qquad (2)$$

When the defocus quantity exceeds the half value width L, a light intensity of the inverse peak becomes high (shallow) by the defocus effect although it is a

continuous change, and the inverse peak pattern starts

becoming shallower. Therefore, in the light intensity

distribution depicted in FIG. 6B, the light intensity

of the inverse peak in the area (trough line) 12a

becomes shallow. As to conditions for the light

intensity of the inverse peak in the area (trough line)

12 to become shallow in the area (trough line) 12b, B >

L is attained along the first direction 16a that the

outgoing radiation pupil of the illumination system 2

is maximum, and B < L is achieved along the first line

16b that the outgoing radiation pupil 2g is minimum.

In this manner, the dimension of the outgoing

radiation pupil 2g of the illumination system 2

required in the modification of the first embodiment,

i.e., the maximum incident angle θmax of the light upon

the phase shifter 1 and the maximum incident angle θmin

of the light upon the phase shifter 1 are defined by

the following conditional expressions (3) and (4).

$$D \times \tan(\theta min) < 1.2 \times (\lambda D/2)^{1/2} \qquad (3)$$

$$D \times \tan(\theta max) > 1.2 \times (\lambda D/2)^{1/2} \qquad (4)$$

FIG. 9 is a view schematically showing a structure

of a crystallization apparatus according to a second

embodiment of the present invention. Although the

second embodiment has a structure similar to that

of the first embodiment, the second embodiment is

basically different from the first embodiment in

that an image forming optical system 5 is included on

a light path between the phase shifter 1 and the

processed substrate 3.   Taking notice of the difference

from the first embodiment, the second embodiment will

be described hereinafter.   It is to be noted that

5   the illustration of an internal structure of the

illumination system 2 is eliminated for clarifying

the drawing in FIG. 9.

In the second embodiment, as shown in FIG. 9,

the processed substrate 3 is set apart from a plane

10   (image surface of the image forming optical system 5)

optically conjugate with the phase shifter 1 by a

predetermined distance along the optical axis.   It is

to be noted that the image forming optical system 5

(and a later-described image forming optical system 6)

15   may be a refraction type optical system, a reflection

type optical system or a refraction/reflection type

optical system.   In the second embodiment based on a

so-called projection defocus method, the same desired

light intensity distribution as that in the first

20   embodiment can be likewise formed on the processed

substrate 3 by using the phase shifter 1, and a crystal

nucleus can be produced at a desired position.

Furthermore, the sufficient lateral growth from the

crystal nucleus can be realized, thereby producing

25   a crystallized semiconductor film with a large particle

size.

In the first embodiment, since the phase shifter 1

is appressed against or in close proximity to the processed substrate 3, the phase shifter 1 may be contaminated due to ablation in the processed substrate 3 and the excellent crystallization may be obstructed. On the contrary, in the second embodiment, since the image forming optical system 5 is interposed between the phase shifter 1 and the processed substrate 3 and a distance between the processed substrate 3 and the image forming optical system 5 is relatively largely assured, the excellent crystallization can be realized without being affected by ablation in the processed substrate 3.

In the first embodiment, since a distance which should be set between the phase shifter 1 and the processed substrate 3 is very small (e.g., several μm to several-hundred μm), a detection light beam used to detect a position is hard to be introduced in a narrow light path between the phase shifter 1 and the processed substrate 3, and it is hence difficult to adjust a distance between the phase shifter 1 and the processed substrate 3. On the contrary, in the second embodiment, since the distance between the processed substrate 3 and the image forming optical system 5 is relatively largely assured, it is easy to introduce the detection light for positional detection in the light path between these members and adjust a positional relationship between the processed substrate 3 and

the image forming optical system 5.

FIG. 10 is a view schematically showing a structure of a crystallization apparatus according to a third embodiment of the present invention. Although the third embodiment has a structure similar to that of the second embodiment, the third embodiment is basically different from the second embodiment in that the phase shifter 1 and the processed substrate 3 are optically conjugatively arranged through an image forming optical system 6. Taking notice of the difference from the second embodiment, the third embodiment will be described hereinafter. It is to be noted that the illustration of an internal structure of the illumination system 2 is likewise eliminated in FIG. 10 for clarifying the drawing.

In the third embodiment, the image forming optical system 6 includes an aperture diaphragm 6a arranged at its pupil (outgoing radiation pupil). The aperture diaphragm 6a has a circular aperture portion (light transmission portion). In this case, a plurality of aperture diaphragms whose apertures portions are different in size are prepared, and the plurality of aperture diaphragms are constituted so as to be switched with respect to the light path. Alterna- tively, the aperture diaphragm 6a may be an iris diaphragm which can continuously or intermittently change a size of a circular aperture portion. In any

case, a size of the aperture portion of the aperture
diaphragm 6a (i.e., an image side numerical aperture of
the image forming optical system 6) is set so as to
generate a predetermined light intensity distribution
on a semiconductor substrate 3.

In the third embodiment based on a so-called
projection NA method, like the first and second
embodiments, a desired light intensity distribution can
be likewise formed on the processed substrate 3 by
using the phase shifter 1, a crystal nucleus can be
generated at a desired position, and the sufficient
lateral growth from the crystal nucleus can be
realized, thereby producing a crystallized semiconduc-
tor film with a large grain size. Moreover, in the
third embodiment, like the second embodiment, the
excellent crystallization can be realized without being
affected by ablation in the processed substrate, and
a positional relationship between the processed
substrate 3 and the image forming optical system 6 can
be adjusted.

FIGS. 11A to 11C are views illustrating a primary
structure and an effect of a crystallization apparatus
according to a modification of the third embodiment.
Although the modification shown in FIGS. 11a to 11C has
a structure similar to that of the third embodiment,
it is basically different from the third embodiment in
that a pupil of the image forming optical system 6 has

a shape that a dimension along one direction and
a dimension along the other direction are substantially
different from each other. Taking notice of the
difference from the third embodiment, the modification
will be described hereinafter with reference to
FIGS. 11A to 11C.

Referring to FIG. 11A, an aperture portion 6b of
an aperture diaphragm 6a arranged at the pupil of the
image forming optical system 6 has an elliptic shape
instead of a circular shape. That is, dimensions of
the pupil 6b of the image forming optical system 6 are
maximum along a first direction (major axis direction)
17a, and it is minimum along a second direction (minor
axis direction) 17b orthogonal to the first direction.
Therefore, the blurring effect becomes minimum
(resolution becomes highest) along the first direction
17a in which the pupil 6b of the image forming optical
system 6 is largest, and the blurring effect becomes
maximum (resolution becomes lowest) along the second
direction 17b in which the pupil 6b is smallest.

As a result, an area 12b affected by the phase
shift lines corresponding to the second direction 17b
has a larger width at a part with a low light intensity
than that of an area 12a affected by the phase shift
lines corresponding to the first direction 17a.
After light irradiation, since this light intensity
distribution is converted into a heating temperature

distribution and a thermal diffusivity is high in a state that the semiconductor is fused, and the temperature distribution is averaged by thermodiffusion in a fusing time. Therefore, there is a strong tendency that a low (deep) temperature state is maintained even after averaged by thermodiffusion as the width at the part with the low light intensity is larger. As a result, the area 12b with the large blurring effect has a low (deep) temperature, and the area 12a with the small blurring effect has a relatively high (shallow) temperature. As described above, in the modification of the third embodiment, a crystal nucleus 13 is generated in an area 11 corresponding to the point type phase shift portion 10e, and the lateral growth does not start along the areas 12a with a high (shallow) temperature, but the lateral growth starts along only the areas 12b with a low (deep) temperature by priority. Consequently, like the modification of the first embodiment, since the lateral growth advances without being affected by adjacent single crystals, larger crystal grains 14 than those in the third embodiment can be produced.

In each of the foregoing embodiments, there is used the phase shifter 1 having the conformation that the four rectangular areas 10a to 10d are arranged so as to be adjacent to each other with one apex 10e in common. However, the present invention is not

restricted thereto, it is possible to use a phase
shifter of which basic unit has a structure that it has
four or more even-numbered phase shift lines which
intersect at a point constituting a phase shift portion
5   and an area on one side and an area on the other
side of each shift line have a phase difference of
approximately 180 degrees. For example, as shown in
FIG. 12, it is possible to use a phase shifter of
which basic unit has a conformation that six or more
10   triangular areas are arranged so as to be adjacent to
each other with one apex in common. In this example,
first to sixth triangular areas 20a to 20f constitute
each basic unit section, a set of the first, third and
fifth areas 20a, 20c and 20e and a set of the second,
15   fourth and sixth areas 20b, 20d and 20f have a phase
difference of 180 degrees. As a result, linear phase
shift portions are formed between the adjacent areas,
and an intersection of these phase shift portions is
a phase shift point area or apex 21. In this case,
20   a crystal nucleus is generated in an area corresponding
to an apex 21 as the phase shift portion, and the
lateral growth occurs along directions corresponding to
the six phase shift lines. The modifications explained
in connection with FIGS. 6A to 6C and FIGS. 11A to 11C
25   can be also applied to the phase shifter depicted in
FIG. 12.

In each of the above-described embodiments, the

description has been given as to the example that the
number of the phase shift lines which intersect at the
phase shift portion is fixed (four or six). However,
the present invention is not restricted thereto, and
5   it is possible to adopt a phase shifter having a
conformation that it has a first phase shift portion at
which even-numbered first phase shift lines intersect
and a second phase shift portion at which even-numbered
second phase shift lines intersect and a plurality of
10   first phase shift portions and a plurality of second
phase shift portions are alternately arranged. For
example, as shown in FIG. 13A, it is possible to use
a phase shifter in which the four phase shift lines
intersect at the first phase shift portion 1a and eight
15   phase shift lines intersect at the second phase shift
portion 1b.

In the phase shifter shown in FIG. 13A, a basic
unit has four square areas. Each area is formed of
two equilateral triangular areas each having a phase
20   difference of 180 degrees. As a result, the first
phase shift portion 1a corresponds to one apex provided
to four triangular areas in common, the adjacent areas
having a phase difference of 180 degrees. The second
phase shift portion 1b corresponds to one apex provided
25   to eight triangular areas in common, the adjacent areas
having a phase difference of 180 degrees. Further, the
first phase shift portions 1a and the second phase

shift portions 1b are alternately arranged in vertical
and horizontal directions. In this case, as shown in
FIG. 13B, there is formed a predetermined light
intensity distribution that a light intensity is

5   minimum in each irradiation area 11b corresponding to
the second phase shift portion 1b at which the eight
phase shift lines intersect, the light intensity is
second minimum in each area 11a corresponding to the
first phase shift portion 1a at which the four phase

10   shift lines intersect and the light intensity is
relatively low in each area (indicated by broken lines
in the drawing) corresponding to the phase shift lines.
That is, a change gradient of the light intensity in
each area 12d extending from the area 11b where the

15   light intensity is minimum toward the area 11a where
the light intensity is second minimum is smaller than a
change gradient of the light intensity in each area 12c
extending from the area 11b where the light intensity
is minimum toward another area 11b where the light

20   intensity is minimum. That is because the light
intensity in the middle portion is lowered since the
area 11a is interposed between two areas 11b. As a
result, as shown in FIG. 13C, a crystal nucleus 13 is
generated at a position on the processed substrate

25   corresponding to the minimum light intensity area
11b, and the lateral growth advances toward the areas
11a where the light intensity is second minimum.

Therefore, in this embodiment, the crystal nucleus generation position and the lateral growth direction can be accurately specified.

FIG. 14A is a view typically showing a light intensity distribution obtained on the processed substrate by using the phase shifter depicted in FIG. 13A by contour lines in the first embodiment. This light intensity distribution typically shows a simulation result obtained based on a specific numerical example. In this numerical example, it is assumed in the phase shifter illustrated in FIG. 13A that dimensions of the square in the basic unit formed of the eight triangular areas are 10 μm × 10 μm, a wavelength λ of the light is 248 nm, a distance D between the phase shifter and the processed substrate is 32 μm and a shape of a surface light source formed to the outgoing radiation pupil (rear focal plane of the second fly-eye lens 2e) of the illumination system 2 is a circle (i.e., a circular illumination).

In this example, such a light intensity distribution as shown in FIG. 14A can be obtained. This distribution has an inverse peak point 11b with a light intensity lower than that at the periphery and four trough lines 12d each of which extends from the inverse peak point 11b toward the periphery and has a lower change gradient of the light intensity than that at the periphery. When this intensity

distribution is seen from the lateral direction, the distribution is as shown in FIG. 14B. Referring to this figure, it can be understood that the light intensity distribution along the trough lines 12d (along the line 14B-14B in FIG. 14A) has inflection points C. This inflection point C is an intersection of the high light intensity portion of the peak in the inverse peak pattern and the linearly extending area with a gentle gradient from the high light intensity portion. Thus, in the modification using the phase shifter shown in FIG. 13A, a crystal nucleus 13 is generated in the area 11b corresponding to the second phase shift portion 1b where the light intensity is minimum.

Furthermore, the lateral growth is hard to start along the area 12c corresponding to the phase shift line extending from one second phase shift portion 1b toward the other second phase shift portion 1b, but the lateral growth starts by priority along the area 12d corresponding to the phase shift line extending from the second phase shift portion 1b toward the first phase shift portion 1a. Since the lateral growth along these areas 12d is not affected by the adjacent lateral growth, relatively large crystal grains 14 can be generated. By using the phase shifter in which the phase shift portions having different numbers of the intersecting phase shift lines are alternately arranged

in this manner, the light intensity distribution
obtained on the processed substrate can be readily
controlled, thereby increasing a degree of freedom in
design. The modifications described in connection with
5   FIGS. 6A to 6C and FIGS. 11A to 11C can be likewise
applied to the phase shifter shown in FIG. 13A.

In the modifications respectively explained with
reference to FIGS. 6A to 6C and FIGS. 11A to 11C, the
outgoing radiation pupil of the illumination system 2
10   and the pupil 6b of the image forming optical system 6
are set to a circular shape. However, the present
invention is not restricted thereto, and it is possible
to set the outgoing radiation pupil of the illumination
system 2 and the pupil 6b of the image forming optical
15   system 6 to have a shape that a dimension along one
direction and a dimension along the other direction
are substantially different from each other (e.g.,
a rectangular).

A description will now be given as to a phase
20   shifter which can be used in a crystallization
apparatus according to a second modification of the
first embodiment with reference to FIGS. 15A to 15C.

FIGS. 15A and 15B are views schematically showing
a structure and an effect of a basic unit of the phase
25   shifter. FIG. 15C is a view typically showing a light
intensity distribution obtained on the processed
substrate by using a phase shifter depicted in

FIG. 15A. Referring to FIG. 15A, a basic unit 30 of
the phase shifter has a first phase shift line 31a
which linearly extends along a vertical direction in
the drawing and a second phase shift line 31b which
meanders along the vertical direction in the drawing, a
left side area 32a in the figure and a right side area
32b in the figure of the first phase shift line 31a and
the second phase shift line 31b has a phase difference
of 180 degrees.

That is, with the transmitted light in the first
area 32a being determined as a reference, a phase
difference of 180 degrees is given to the transmitted
light in the second area 32b. Specifically, when the
phase shifter is formed of, e.g., quartz glass having
a refractive index of 1.5 with respect to the light
having a wavelength of 248 nm, a step of 248 nm is
given between the first area 32a and the second
area 32b.

When the phase shifter and the processed substrate
are arranged so as to be appressed against each other,
a light intensity distribution with a low light
intensity is formed only at a part corresponding to
the phase shift lines 31a and 31b. However, since
the phase shifter 1 and the processed substrate 3 are
arranged in close proximity to each other in the first
embodiment shown in FIG. 3, there is formed a light
intensity distribution with an inverse peak pattern

that a light intensity is low in line areas 33a and 33b corresponding to the phase shift lines 31a and 31b and the light intensity is suddenly increased along a direction orthogonal to the line areas 33a and 33b by a so-called defocus effect (blurring effect) as shown in FIG. 15C.

In FIG. 15C, a light intensity distribution indicated by reference character A-A represents a light intensity distribution along a direction corresponding to a direction indicated by a line A-A in FIG. 15A (direction orthogonal to the first phase shift line 31a), and a light intensity distribution indicated by reference character B-B represents a light intensity distribution along a direction corresponding to a direction indicated by a line B-B in FIG. 15A (direction orthogonal to the second phase shift line 31b). As shown in FIG. 15C, the light intensity in the line area 33b corresponding to the meandering second phase shift line 31b is substantially higher than the light intensity in the line area 33a corresponding to the linear first phase shift line 31a. That is because the light intensity distribution in a range of a shaped width W as a gap between a minimum position and a maximum position of meandering (see FIG. 15A) is averaged by a synergistic effect of meandering of the second phase shift line 31b and the defocus effect (blurring effect), and the light intensity of the

inverse peak becomes high (shallow).

That is, as the shaped width W of meandering of the second phase shift line 31b becomes larger, the light intensity in the line area 33b corresponding to the second phase shift line 31b is increased. Further, the light intensity is averaged on the boundary between the line area 33a and the line area 33b, and it smoothly varies from a high value to a low value. As described above, in the light intensity distribution on the processed substrate 3, the light intensity is minimum in the line area 33a corresponding to the first phase shift line 31a, and a trough line in which a change gradient of the light intensity is lower than that at the periphery is formed toward the line area 33b corresponding to the second phase shift line 31b from the line area 33a corresponding to the first phase shift line 31a. Therefore, in this modification of the first embodiment, a crystal nucleus 34 is generated on the line area 33a corresponding to the linear first phase shift line 31a as shown in FIG. 15B.

Moreover, since the light intensity distribution in the trough line formed toward the second phase shift line 31b from the first phase shift line 31a does not involve irregular undulations (wavelike distribution that an increase and a decrease in light intensity are repeated), the lateral growth which has started along the trough line from the crystal nucleus 34 does not

stop in mid course, and a crystal grain 35 with a large

particle size is generated. As described above, in

this example based on a so-called proximity method

(defocus method), a crystal nucleus can be generated at

5   a position desired to some extent by a combination of

the linear phase shift line and the meandering phase

shift line, and the sufficient lateral growth from the

crystal nucleus can be realized in a desired direction,

thereby producing a crystallized semiconductor film

10   with a large particle size.

FIG. 16A and 16B are views schematically showing a

structure and an effect of a phase shifter which can be

used in a third modification of the first embodiment.

Although this phase shifter has a structure similar

15   to that of the phase shifter used in the second

modification, it is basically different from the first

embodiment in that the first phase shift line 31a

is not linear but meandering with a shaped width

substantially smaller than the shaped width W of the

20   second phase shift line 31b. Taking notice of the

difference from the second modification, the third

modification will now be described.

Referring to FIG. 16A, a basic unit part 30a of

the phase shifter has a first phase shift line 31a

25   which meanders with a relatively small shaped width

along a vertical direction in the drawing and a second

phase shift line 31b which meanders with a relatively

large shaped width W along the vertical direction in the drawing, and an area 32a on the left side in the figure and an area 32b on the right side in the figure with the first phase shift line 31a and the second phase shift line 31b therebetween have a phase difference of 180 degrees. In this case, since a light intensity in the line area corresponding to the phase shift line is increased as the shaped width of meandering becomes larger as described above, the light intensity in the line area 33b corresponding to the second phase shift line 31b is substantially higher than the light intensity in the line area 33a corresponding to the first phase shift line 31a.

As a result, in the light intensity distribution on the processed substrate 3, the light intensity in the line area 33a corresponding to the first phase shift line 31a is minimum, and a trough line with a lower change gradient of the light intensity than that at the periphery is formed toward the line area 33b corresponding to the second phase shift line 31b from the line area 33a corresponding to the first phase shift line 31a. Therefore, a crystal nucleus 34 is generated on the line area 33a corresponding to the first phase shift line 31a, the lateral growth which has started from the crystal nucleus 34 along the trough line does not stop in mid course, and a crystal grain 35 with a large particle size is produced.

That is, in the phase shifter shown in FIG. 16A, a crystal nucleus can be generated at a position desired to some extent by a combination of the phase shift line which meanders with a large shaped width and the phase shift line which meanders with a small shaped width (by modulation of the shaped widths of the meandering phase shift lines), and the sufficient lateral growth can be realized from the crystal nucleus, thereby producing a crystallized semiconductor film with a large particle size.

FIGS. 17A and 17B are views schematically showing a structure and an effect of a phase shifter used in a crystallization apparatus according to a fourth modification of the first embodiment. Although the phase shifter according to this fourth modification has a structure similar to that of the phase shifter according to the second modification, it is basically different from the phase shifter according to the second modification in that a linear third phase shift line 31c orthogonal to the first phase shift line 31a is additionally provided. Taking notice of the difference from the first embodiment, the fourth modification will be described hereinafter.

Referring to FIG. 17A, a basic unit 30b of the phase shifter has a first phase shift line 31a which linearly extends along a vertical direction in the drawing, a second phase shift line 31b which meanders

along the vertical direction in the drawing, and

a third phase shift line 31c which linearly extends in

a horizontal direction in the drawing and crosses the

first phase shift line 31a. Areas 32d and 32c on the

left side in the figure and areas 32a and 32d on the

right side in the figure with the first phase shift

line 31a and the second phase shift line 31b

therebetween have a phase difference of 180 degrees,

and areas 32a and 32b on the upper side in the figure

and areas 32c and 32d on the lower side in the figure

have a phase difference of 180 degrees. That is, the

first area 32a and the third area 32c are in phase,

and the second area 32b and the fourth area 32d have

a phase difference of 180 degrees. In this case,

an intersection 31d of the first phase shift line 31a

and the third phase shift line 31c constitutes a phase

shift portion like the phase shifter shown in FIG. 4A.

As a result, in the light intensity distribution

on the processed substrate 3, the light intensity is

minimum in the area 33d corresponding to the phase

shift portion 31d, and a trough line that a change

gradient of the light intensity is lower than that at

the periphery is formed toward the line area 33b

corresponding to the second phase shift line 31b from

the line area 33a corresponding to the first phase

shift line 31a. As shown in FIG. 17B, therefore,

a nucleus 34 is formed the area 33d corresponding to

the phase shift portion 31d, the lateral growth which has started from the crystal nucleus 34 along the trough line does not stop in mid course, the a crystal grain 35 with a large particle size is produced.

5   That is, in this modification, and a crystal nucleus 34 can be more accurately generated at a desired position than the second and third modifications by additionally providing the linear third phase shift line 31c orthogonal to the first phase shift line 31a.

10   FIG. 18 is a view illustrating a size of a shaped width W required for the meandering second phase shift line in the second to fourth modifications. Referring to FIG. 18, in the light intensity distribution formed on the processed substrate by the phase shifter, a half value width L of the inverse peak pattern obtained

15   along a direction orthogonal to the phase shift line with the linear shift line at the center can be represented by the above-described expression (1).

In order to increase the light intensity in the

20   line area 33b corresponding to the meandering second phase shift line 31b to a necessary degree by the above-described light intensity averaging effect, it is preferable that the shaped width W of the second phase shift line 31b is larger than the half value width L,

25   i.e., that the following conditional expression (5) is satisfied.

$$W > 1.2 \times (\lambda D/2)^{1/2} \qquad\qquad (5)$$

However, the light intensity averaging effect of the present invention can be sufficiently obtained when the shaped width W of the second phase shift line 31b satisfies the following conditional expression (6) obtained by multiplying a value on the right side of an inequality sign in the conditional expression (5) by a coefficient 0.5.

$$W > 0.6 \times (\lambda D/2)^{1/2} \qquad (6)$$

It can be readily understood by persons skilled in the art that the phase shifter described in connection with the second to fourth modifications of the first embodiment can be also used as the phase shifter of the crystallization apparatus according to the second to third embodiments.

When the second to fourth phase shifters of the first embodiment are used as the modification of the third embodiment based on the projection NA method, the blurring effect can be obtained on the processed substrate by setting the image side numerical aperture NA of the image forming optical system 6 to be small. A blurring quantity B obtained by a reduction in resolution can be represented by the following expression (7).

$$B = 0.61 \times \lambda/NA \qquad (7)$$

A constant 0.61 in the expression (7) indicates a distance (radius) required to obtain zero first from the center in the light intensity distribution acquired

in case of the complete coherent illumination. In the
actual optical system, since the complete coherent
illumination cannot be obtained, a value of this
constant is different, but it is a value of approxi-
mately 1. In order to increase the light intensity in
the line area 33b corresponding to the meandering
second phase shift line 31b to a necessary degree by
the above-described blurring effect, it is preferable
that the shaped width W of the second phase shift line
31b is larger than the blurring quantity B, i.e., that
the following conditional expression (8) is satisfied.

$$W > 0.61 \times \lambda/NA \tag{8}$$

However, the blurring effect of the present
invention can be sufficiently obtained when the
shaped width W of the second phase shift line 31b
satisfies the following conditional expression (9)
acquired by multiplying a value on the right side of
an inequality sign in the conditional expression (8) by
a coefficient 0.5.

$$W > 0.305 \times \lambda/NA \tag{9}$$

Furthermore, in each embodiment and each
modification mentioned above, the phase shift line
which meanders substantially in the zigzag form with
triangular waves is described as the meandering phase
shift line. However, the present invention is not
restricted thereto, and it is possible to adopt various
modifications of the meandering phase shift line, e.g.,

a phase shift line which meanders in the sine curve
form or a step-like phase shift line which entirely
meanders in the zigzag form or the sine curve form.
At this time, an amplitude and a pitch of meandering

5   do not have to be the same in all the examples.
For example, it is possible to employ meandering that
the amplitude becomes large as distanced from the phase
shift portion or meandering that the pitch becomes
small or vice versa.

10   In each of the foregoing embodiments, although
the light intensity distribution can be calculated on
a design stage, it is desirable to observe and confirm
the light intensity distribution on the actual
processed surface (exposed surface). In order to

15   realize this, zooming the processed surface by the
optical system and performing input by an imaging
element such as. a CCD can suffice. When the light to
be used is an ultraviolet light beam, since the optical
system is restricted, a fluorescent screen may be

20   provided to the processed surface in order to convert
the light into a visible light beam.

         FIGS. 19A to 19E are process cross-sectional views
showing processes to manufacture an electronic device
by using a crystallization apparatus according to each

25   embodiment. As shown in FIG. 19A, the processed
substrate 3 is prepared by forming an underlying film
81 (e.g., SiN having a film thickness of 50 nm and an

SiO_2 laminated film having a film thickness of 100 nm) and an amorphous (or polycrystal) semiconductor film 82 (e.g., Si, Ge, SiGe or the like having a film thickness of approximately 50 nm to 200 nm) on a transparent

5   insulating substrate 80 (e.g., alkali glass, quartz glass, plastic, polyimide or the like) by a chemical vapor deposition method or a sputtering method. Then, as indicated by arrows, the crystallization apparatus according to each embodiment is used to irradiate a

10   part or all of the surface of the amorphous semiconductor film 82 with a laser beam 83 (e.g., a KrF excimer laser beam or an XeCl excimer laser beam) modulated to have a light intensity distribution with an inverse peak pattern by the phase shifter as described above.

15   As a result, as shown in FIG. 19B, the amorphous semiconductor of the amorphous semiconductor film 82 is crystallized, and a crystallized semiconductor film (a polycrystal semiconductor film or a monocrystal semiconductor film) 84 having crystal grains with

20   a larger particle size is generated. Subsequently, as shown in FIG. 19C, the polycrystal semiconductor film or the monocrystallized semiconductor film 84 is processed into an island-shaped semiconductor film 85 by using the photolithography technology, and

25   an SiO_2 film having a film thickness of 20 nm to 100 nm as a gate insulating film 86 is formed on the monocrystallized semiconductor film 85 and the

underlying film 81 by using the chemical vapor
deposition method or the sputtering method. Moreover,
as shown in FIG. 19D, a gate electrode 87 (e.g.,
silicide or MoW) is selectively formed on the gate

5   oxide film 86 so as to correspond to the central part
of the crystallized semiconductor film 85. Then,
as indicated by arrows, impurity ions 88 (phosphor
incase of an N channel transistor, boron in case of a
P channel transistor) are selectively implanted into

10   the crystallized semiconductor film 85 with the gate
electrode 87 being used as a mask. Thereafter,
annealing processing (e.g., one hour at 450°C) is
performed in a nitrogen atmosphere, the impurities in
the crystallized semiconductor film 85 are activated,

15   and a source area 91 and a drain area 92 are formed
with a channel 90 therebetween as shown in FIG. 19E.
Then, an interlayer insulating film 89 is formed on the
gate oxide film 86 and the gate electrode 87. Contact
holes are formed to the interlayer insulating film 89

20   and the gate oxide film 86, and a source electrode 93
and a drain electrode 94 connected with the source area
91 and the drain area 92 are formed.

       In the above-described processes, a position of
the channel 90 is set in accordance with a position

25   of the crystal with a large particle size of the
crystallized semiconductor film 84 generated in the
processes shown in FIGS. 19A and 19B. This positioning

can be readily and assuredly performed since the
crystal nucleus formation position accuracy is high
in the above-described crystallization technology
according to the present invention. As a result, it is
5   possible to form a polycrystal semiconductor transistor
or a monocrystal semiconductor transistor having the
channel 90 with the high electron mobility can be
formed.   The thus manufactured thin film transistor
can be applied to a drive circuit for, e.g., a liquid
10   crystal display or an EL (electroluminescence) display
or an integrated circuit of, e.g., a memory (SRAM or
DRAM) or a CPU.

Although the above has described as to the case
that the crystallization technology according to the
15   present invention is applied to manufacture of the thin
film transistor, this technology can be also applied to
manufacture of any other semiconductor element.

Additional advantages and modifications will
readily occur to those skilled in the art. Therefore,
20   the invention in its broader aspects is not limited to
the specific details and representative embodiments
shown and described herein. Accordingly, various
modifications may be made without departing from the
spirit or scope of the general invention concept as
25   defined by the appended claims and their equivalents.